

# QCD corrections to FCNC single top production at HERA

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## Abstract

We calculate first-order QCD corrections to the cross section for single top quark production mediated by flavor changing neutral currents (FCNC) in  $ep$  collisions at the HERA collider. We find that the uncertainty due to the choice of the QCD scale is significantly reduced. This study is motivated by the current experimental work for limits on the FCNC single top cross section.

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The top quark is the only known fermion which has a mass close to the scale of the electroweak symmetry breaking (EWSB). Hence, the study of the electroweak properties of the top-quark sector may shed some light on the mechanism responsible for the EWSB. Moreover, deviations from the Standard Model predictions might be expected in the large mass top sector. Thus, single top quark physics could probe various physics beyond the Standard Model: anomalous gluon-top quark couplings [1], anomalous  $Wtb$  couplings [2], new strong dynamics [3], flavor changing neutral current (FCNC) couplings [4, 5], R-parity violating SUSY effects [6], CP-violation effects [7], and effects of Kaluza-Klein excited  $W$ -bosons [8].

Single top quark physics is a very promising place to test the FCNC effects for  $tqV$  couplings, where  $q = u$ - or  $c$ -quark and  $V = \gamma, Z, g$ . Those couplings effectively appear in Supersymmetry or in the scenario where new dynamics takes place in the fermion mass generation. The effective Lagrangian involving such couplings of a  $t, q$  pair to massless bosons is the following:

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda} [\kappa_{tq\gamma} e \bar{t} \sigma_{\mu\nu} q F^{\mu\nu} + \kappa_{tqg} g_s \bar{t} \sigma_{\mu\nu} \frac{\lambda^i}{2} q G^{i\mu\nu}] + h.c., \quad (1)$$

where  $F^{\mu\nu}$  and  $G^{i\mu\nu}$  are the usual electromagnetic and gluon field tensors with respective FCNC  $\kappa_{tq\gamma}$  and  $\kappa_{tqg}$  couplings,  $\lambda^i$  are the Gell-Mann matrices, and  $\sigma_{\mu\nu} = (i/2)(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$  with  $\gamma_\mu$  the Dirac matrices. It was found [5] that the strength for the anomalous  $tq\gamma$  ( $tqg$ ) coupling may be probed to  $\kappa_{tq\gamma}/\Lambda = 0.092 \text{ TeV}^{-1}$  ( $\kappa_{tqg}/\Lambda = 0.026 \text{ TeV}^{-1}$ ) at the Tevatron with  $2 \text{ fb}^{-1}$  of data and  $\kappa_{tq\gamma}/\Lambda = 0.013 \text{ TeV}^{-1}$  ( $\kappa_{tqg}/\Lambda = 0.0061 \text{ TeV}^{-1}$ ) at the LHC with  $10 \text{ fb}^{-1}$  of data. Efficiencies from [5] can be used to put the limits on  $\kappa_{tq\gamma}$ ,  $\kappa_{tqg}$  couplings ( $\Lambda = m_{\text{top}}$ , 95%CL) at the Tevatron Run 2:  $\kappa_{tq\gamma} < 0.24$ ,  $\kappa_{tqg} < 0.074$ . However, better limits (of the order of 0.044 at Run 2) on these couplings  $\kappa_{tq\gamma}$  are expected to come from the study of decays  $t \rightarrow q\gamma$  of pair-produced tops. This process already allows to derive an upper bound  $\kappa_{tq\gamma} < 0.14$  from the CDF data taken at Tevatron Run 1, which is slightly better than the limit obtained by studying  $ee \rightarrow tq$  in LEP2 data [9].

It is interesting to note that HERA should provide a very good sensitivity on the FCNC  $tq\gamma$  coupling via single top production in the process  $eu \rightarrow et$  with the respective diagram shown in Fig. 1.

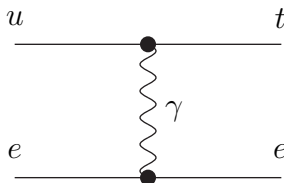


Figure 1: Diagram for the FCNC single top quark production at HERA

Even at present ZEUS+H1  $160 \text{ pb}^{-1}$  integrated luminosity, in the absence of a signal, the limit should be  $\kappa_{tq\gamma} < \sim 0.05$ , which is significantly better than the current most stringent bound [10]. Alternatively, the relatively large ( $\sim 1 \text{ pb}$ ) cross section still allowed by the current CDF limit on  $\kappa_{tq\gamma}$  would lead to many single top events. It is interesting to note that H1 observed some events with a high  $p_T$  isolated lepton ( $e$  or  $\mu$ ), together with missing energy and a large  $p_T$  hadronic final

state. Such a final state would be expected from single top events, where the  $W$  coming from the top undergoes a semileptonic decay [11].

However there is a big ambiguity due to the choice of the QCD scale. FCNC single top quark production at HERA is a  $t$ -channel process involving a massive final state top quark. The effective QCD scale is unknown: one can not use  $Q^2 = -t = (p_e - p_{e'})^2$  as the scale, for example, since the kinematical distributions concentrated around  $Q_{min}^2$  are of the order of  $m_e^2 \simeq 10^{-7} \text{ GeV}^2$ . This value of  $Q^2$  for the parton structure function has no sense.

At the same time  $Q^2 = m_{top}^2$  seems a little large for this process with such a small value of the  $t$  variable. For the  $Q$  scale between  $\simeq 5 \text{ GeV}$  (minimal  $Q$  for the parton density) and  $m_{top} = 175 \text{ GeV}$  the Born cross section varies by a factor of 2. For example, the cross section for a center-of-mass (CM) energy  $\sqrt{S} = 300 \text{ GeV}$  and CTEQ5M parton densities [12] at  $Q = m_{top}$  is equal to 0.39 pb and at  $Q = 5 \text{ GeV}$  equal to 0.78 pb. This is not surprising for the given very different QCD scales. First-order QCD corrections should stabilize the cross section with variation of the QCD scale. This is the subject of this letter.

We calculate the first-order QCD corrections to the FCNC single top production using the eikonal approximation. Since the top is very heavy, this process at HERA is dominated by the threshold region where the eikonal approximation, which describes soft gluon emission, is valid. We calculate one-loop eikonal diagrams using techniques developed for top pair production and other QCD hard scattering cross sections [13, 14, 15]. It is well known that near threshold the eikonal corrections reproduce the dominant terms of the full QCD corrections for a variety of cross sections both analytically and numerically [13, 15]. It is also known from resummation studies that these corrections exponentiate, but we will not pursue this topic in this letter. We define the usual Mandelstam invariants for the process  $e(p_e) + u(p_u) \rightarrow e(p_{e'}) + t(p_t)$  as  $s = (p_e + p_u)^2$ ,  $t = (p_t - p_u)^2$ , and  $u = (p_t - p_e)^2$ . We also define a variable  $s_2 = s + t + u - m_t^2 - 2m_e^2$ , with  $m_t$  and  $m_e$  the top quark and electron masses, respectively. At threshold  $s_2 = 0$ . We find that the first-order QCD corrections in the  $\overline{\text{MS}}$  scheme take the form

$$\begin{aligned} \frac{d\hat{\sigma}_{eu \rightarrow et}^{(1)}}{dt du} = & F_{eu \rightarrow et}^B \frac{\alpha_s(\mu_R^2)}{\pi} \left\{ 2C_F \left[ \frac{\ln(s_2/m_t^2)}{s_2} \right]_+ \right. \\ & + \left[ \frac{1}{s_2} \right]_+ C_F \left[ -1 - 2 \ln \left( \frac{-u + m_e^2}{m_t^2} \right) + 2 \ln \left( \frac{m_t^2 - t}{m_t^2} \right) - \ln \left( \frac{\mu_F^2}{m_t^2} \right) \right] \Big\} \\ & + \delta(s_2) \left[ -\frac{3}{4} + \ln \left( \frac{-u + m_e^2}{m_t^2} \right) \right] C_F \ln \left( \frac{\mu_F^2}{m_t^2} \right) \Big\} , \end{aligned} \quad (2)$$

where  $\mu_F$  and  $\mu_R$  are the factorization and renormalization scales, respectively, and the Born term,  $F_{eu \rightarrow et}^B$ , is defined by

$$F_{eu \rightarrow et}^B = \frac{\kappa_\gamma^2 e^4}{2\pi m_t^2 t^2 (s - m_e^2)^2} \left\{ -t \left[ 2m_e^4 + m_t^4 - 2s^2 + (2s + t)(2s - m_t^2 - 2m_e^2) \right] - 2m_e^2 m_t^4 \right\} . \quad (3)$$

The Born differential cross section is  $d\hat{\sigma}_{eu \rightarrow et}^B/(dt du) = F_{eu \rightarrow et}^B \delta(s_2)$ . The plus distributions are defined by their integral with any smooth function  $\phi$ , such as the parton densities, as  $\int_0^{m^2} ds_2 \phi(s_2) [(\ln^n(s_2/m^2))/s_2]_+ = \int_0^{m^2} ds_2 [(\ln^n(s_2/m^2))/s_2] [\phi(s_2) - \phi(0)]$ .

In Figs. 2(a),(b) we present the Born and one loop results for  $\sqrt{S} = 300$  and 318 GeV, respectively, as functions of the QCD scale  $Q = \mu_F = \mu_R$ . We note the stabilization of the cross

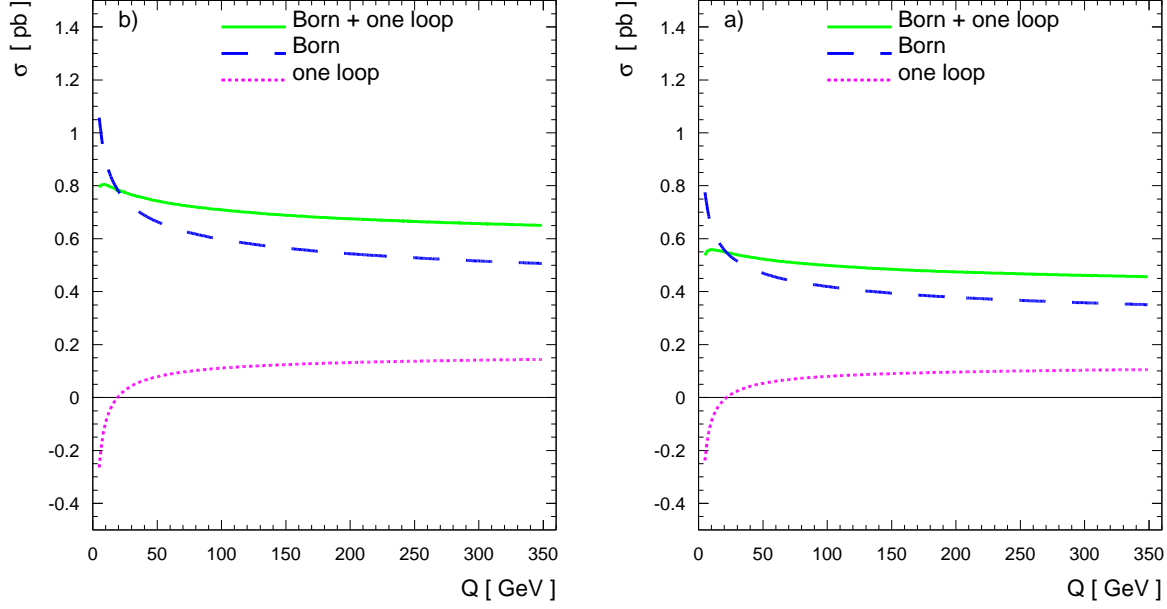


Figure 2: Born, one loop, and Born+one loop cross section for FCNC single top quark production at HERA with  $m_{\text{top}} = 175$  GeV and  $\kappa_{t\gamma} = 0.1$  for (a)  $\sqrt{S} = 300$  and (b) 318 GeV.

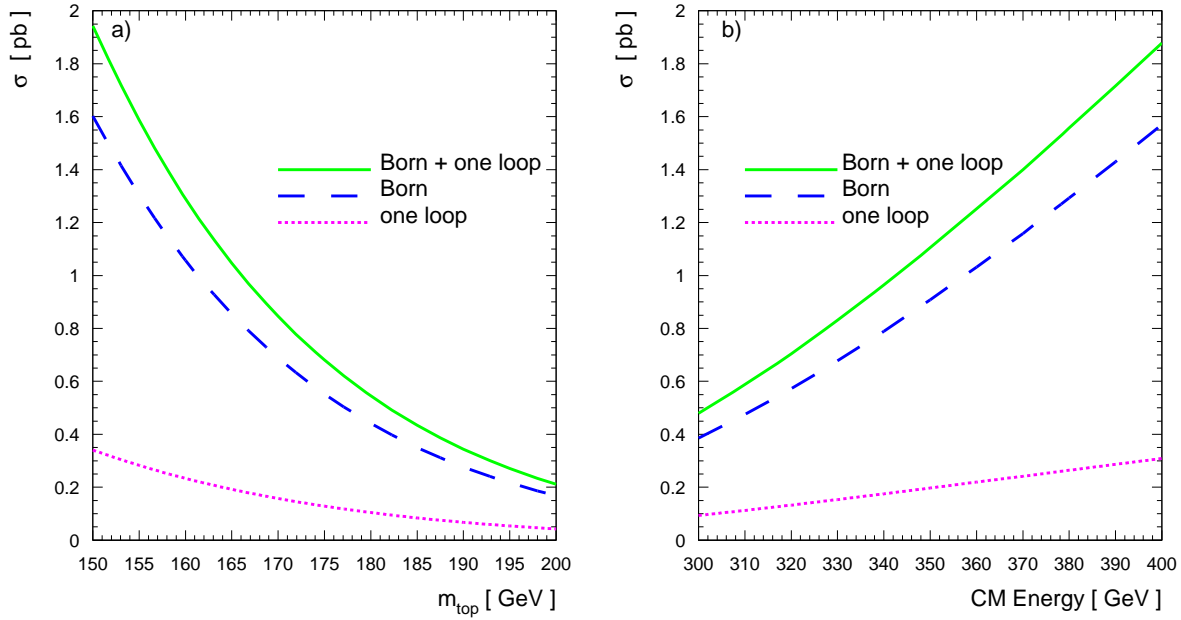


Figure 3: Born, one loop, and Born+one loop cross section for the FCNC single top quark production at HERA with  $Q = m_{\text{top}}$  and  $\kappa_{t\gamma} = 0.1$  versus (a) the top quark mass with  $\sqrt{S} = 318$  GeV and (b) the CM energy with  $m_{\text{top}} = 175$  GeV.

section with scale variation when the QCD corrections are included. Since the Born+one loop results are very stable throughout the  $Q$  region, it makes little difference what scale we choose for the central value of  $Q$ . We decided to use  $m_{\text{top}}$  for the central value and vary the scale by a factor of two, as commonly done. We found that for  $\sqrt{S} = 300$  GeV the QCD corrected cross section is  $\sigma_{eu \rightarrow et}^{B+1\text{-loop}} = 0.48 \pm 0.02$  pb and for  $\sqrt{S} = 318$  GeV it is  $\sigma_{eu \rightarrow et}^{B+1\text{-loop}} = 0.68_{-0.03}^{+0.04}$  pb. The  $\kappa_{tu\gamma}$  parameter was chosen to be 0.1.

One should notice that we did not include in our result the uncertainty due to the top quark mass. For illustrative purposes we present the Born, one-loop, and Born+one loop cross sections as functions of the top quark mass and CM energy in Figs. 3(a) and (b), respectively. A variation of the top quark mass by  $\pm 5$  GeV causes over 20% uncertainty in the total cross section. The role of the CM energy is very important in this kinematical region, where the quark luminosity quickly increases with the energy: the 6% increase of the CM energy ( $300 \rightarrow 318$  GeV) leads to a 40% increase of the total cross section.

The HERA collider has the potential to establish the best limit on the FCNC electromagnetic coupling involving top and  $u$ - quarks. Keeping in mind also the observation of events with isolated leptons, missing transverse momentum, and a jet with large transverse momentum at HERA (which motivated the experimental studies), an accurate limit on the FCNC coupling based on the QCD corrected cross section is very important.

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